Modeling of Argon in the Lunar Exosphere

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Detection of Argon in Lunar Atmosphere

- Argon was detected by LACE, a mass spectrometer deployed at lunar surface during Apollo 17 mission (1972).
- LACE measured only flux of downcoming particles, so concentration can be retrieved only if one assumes a Maxwellian distribution:

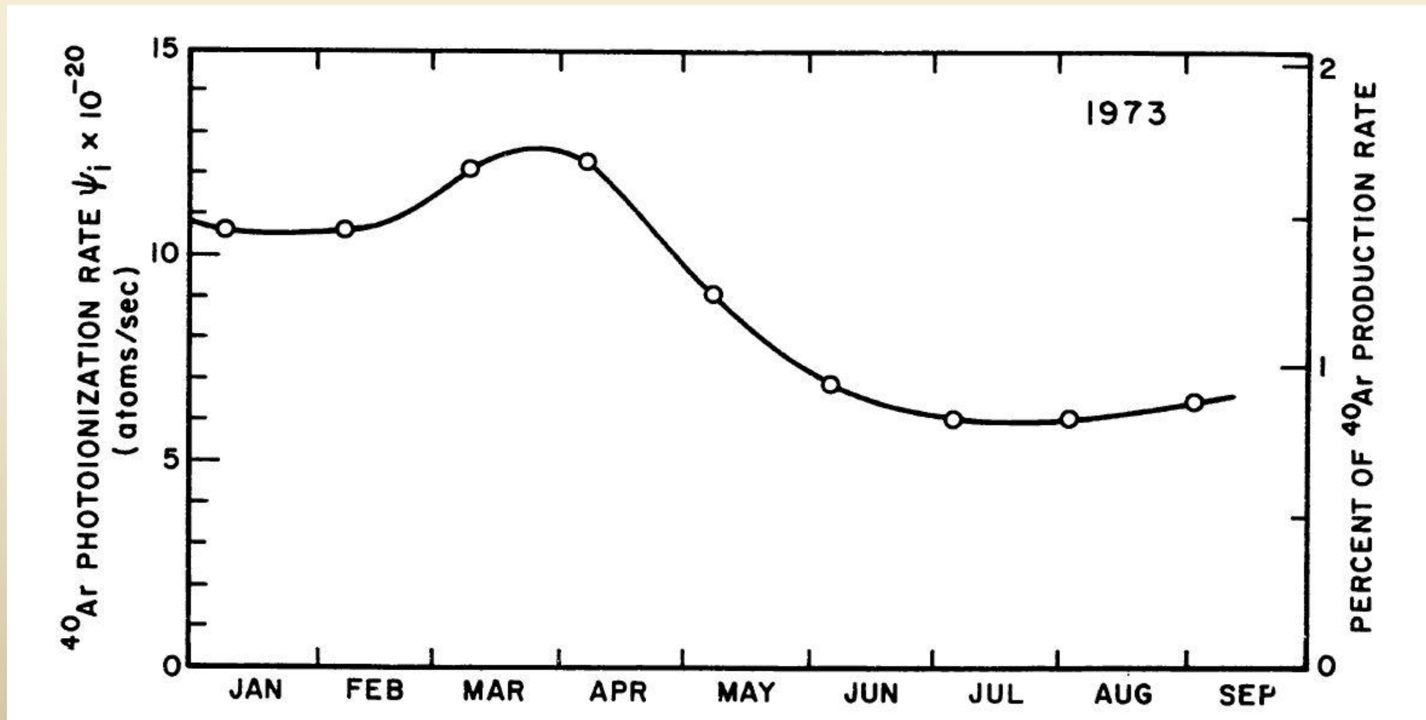
  $\phi = n\langle v\rangle/4$ (Hodges 1973)

- Fig. 1: the LACE mass spectrometer was deployed at the lunar surface at ~22° N during Apollo 17 mission.

Detection of Argon in Lunar Atmosphere

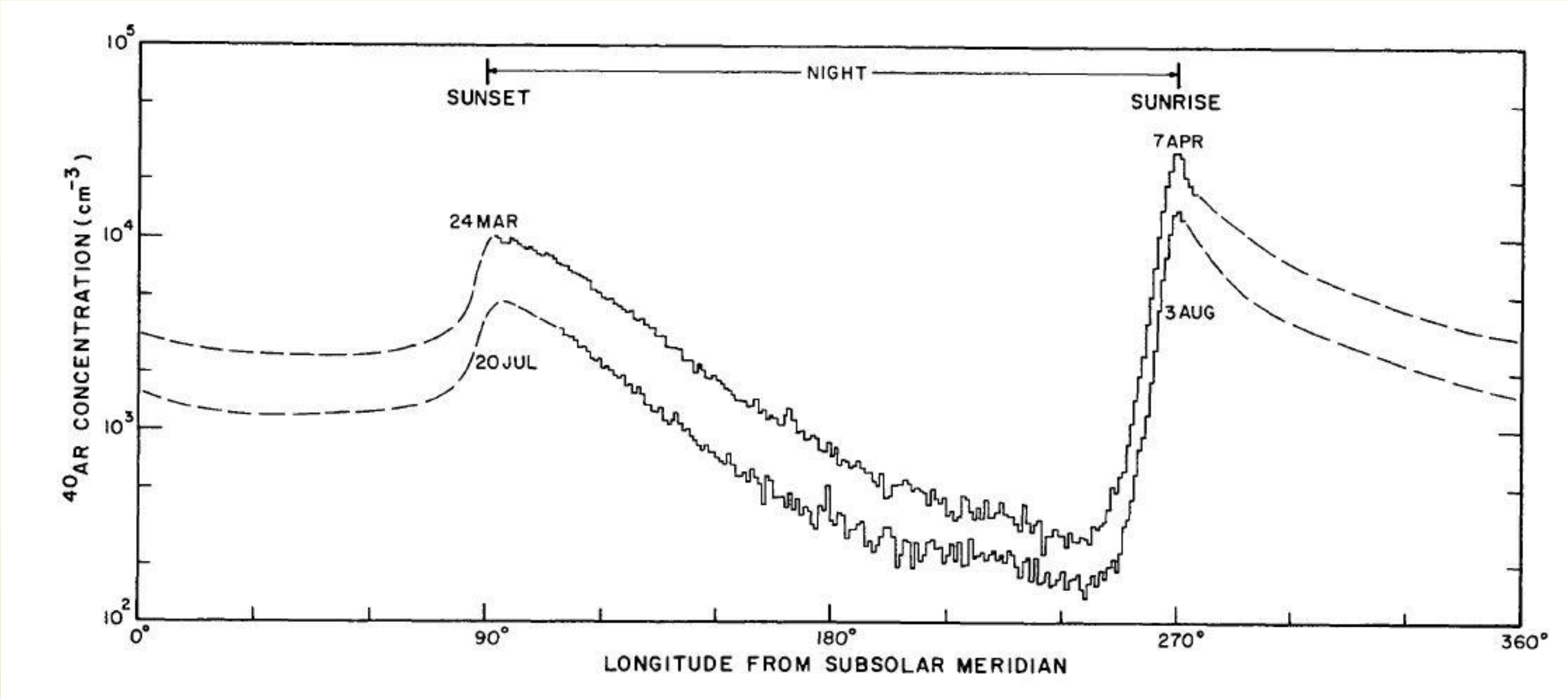
- Argon concentration showed short-term variations, but an overall decrease of argon atmospheric density during the 9 lunations was observed.
- Concentration is related to the photo-ionization rate :
  $\phi = 4.4 \times 10^{16} \times n_{sunrise}$ atoms s^{-1} (*Hodges & Hoffman 1974*)

- Fig. 2: The photo-ionization rate of Argon ,which is a proxy for the density of Argon at LACE position (22° N)



Detection of Argon in Lunar Atmosphere

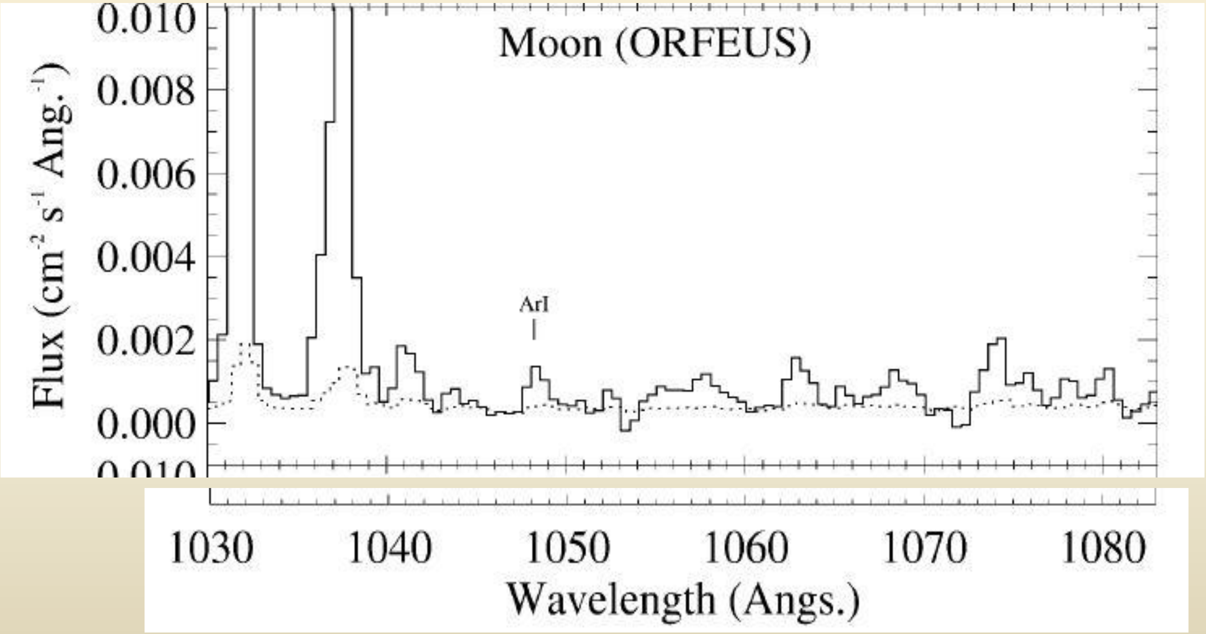
- Night side profile show pattern of a condensable gas.
- Argon density 4 months later is 2.7x smaller.
- Fig. 3: diurnal profile of argon density measured by LACE during two different lunations. Sunset is at 90° longitude, midnight is at 180° longitude, and sunrise is at 270° longitude. The lower curve was measured 4 months later than the higher curve.



(*Hodges & Hoffman 1974*)

LRO-LAMP's Recent Non-detection of Argon in Lunar Exosphere

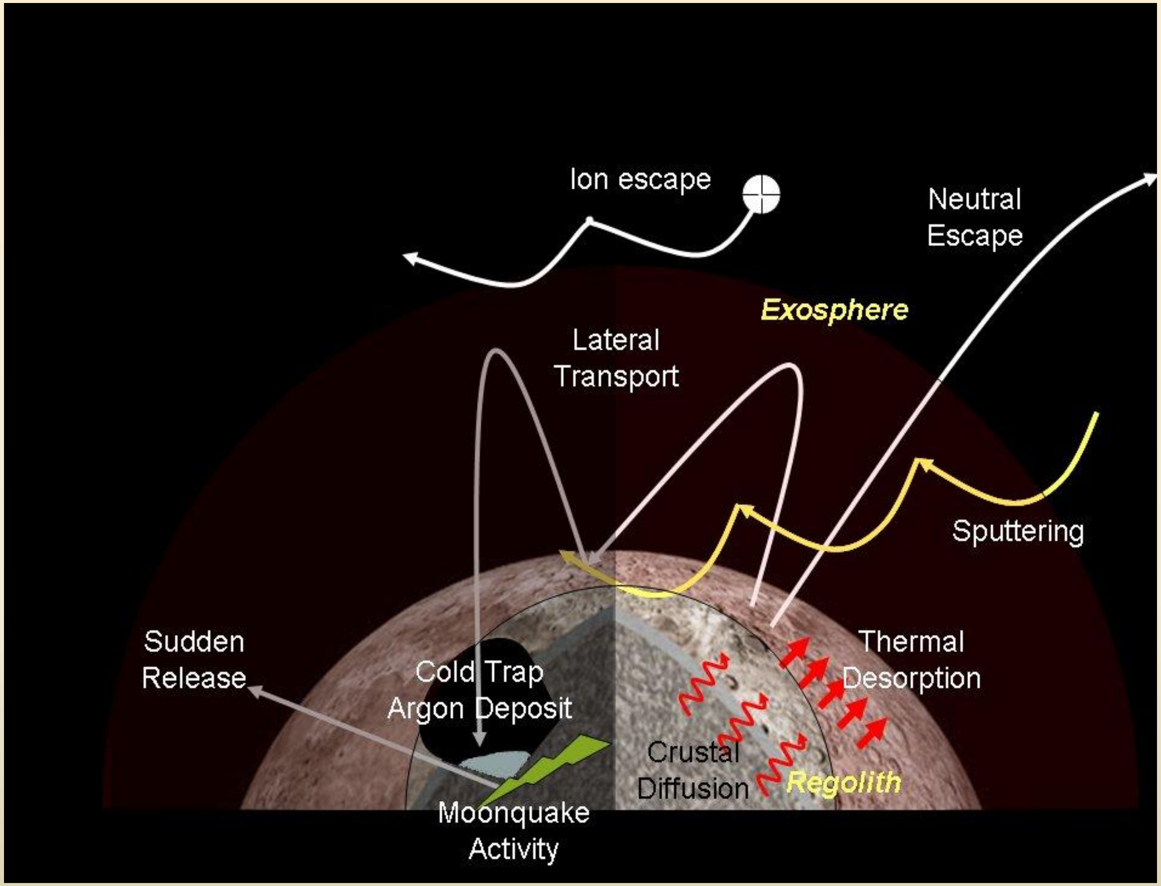
- Subsequent attempts to detect argon in lunar exosphere by remote-sensing did not give positive results (see Fig. 4).
- Fig. 4: lunar spectrum by Flynn 1998 where a slight emission from Ar 1048 A line is apparent. Subsequent studies by the same group (*Parker et al., 1999*) revealed this emission not to be realistic.



- Last upper limit from *Cook et al. 2013* is 2.3x10^{4} cm^{-3}. LAMP provides a 1.5 times lower upper estimate than from previous observations.

Origin of Argon in Lunar Atmosphere

- Why Argon is important? Because, contrary to ^{36}Ar, ^{40}Ar comes from radiogenic decay of ^{40}K within the interior (*Hayman & Yaniv 1970, Manka & Michel 1971*).
- It is a truly native elements of lunar interior.
- Argon behavior might resemble that of other volatiles on the Moon.
- A simulation has been performed to study transport, losses, and storage of Argon to the cold traps.
- Fig. 5: various processes that lead to loss or storage of Argon in cold traps.



Argon simulation:

- 3D Monte Carlo particle approach as used in *Leblanc & Chaufray, 2011;*
- One single ejection at the beginning (simulating e.g. moonquake);
- Follows the trajectory of particles until annihilation or implantation to cold traps;
- Particles thermalize with the surface. Therefore, the accommodation factor, a, is equal to 1: $\alpha = \left(\frac{E_{out} - E_{in}}{E_T - E_{in}} \right) = 1$

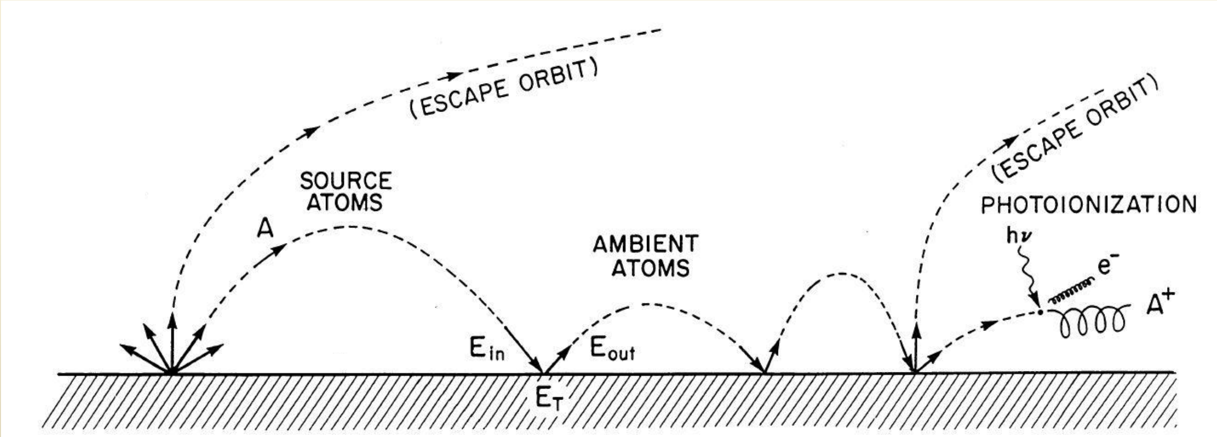


Fig. 6: our approach for tracking the ballistic hops and accommodation of particles to the surface is similar to the model of *Smyth and Marconi [1995]*.

Argon simulation: Temperature map

- Our code utilizes a LRO/Diviner Temperature map as representative of the diurnal pattern. This is an improvement over previous analytical approaches, especially to simulate Permanently Shaded Surfaces (PSRs).
- Once a particle sticks to the surface, it resides for some time before being ejected.. The residence time is taken from Hodges 1982: $t_{res} = \frac{C}{T^2} \exp\left(-\frac{Q \cdot 4.18}{RT}\right)$
  with Q activation energy (cal mole^{-1}) and C a constant (s K^{-2}); 4.18 takes into account the conversion calories – Joule and R is the gas constant.

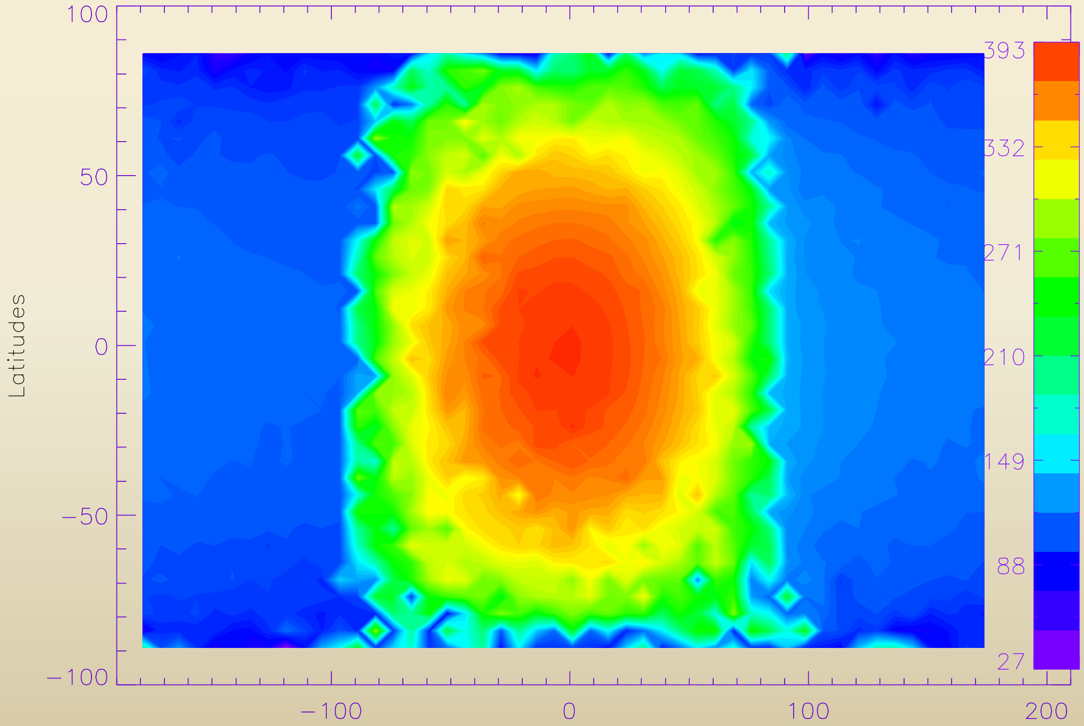
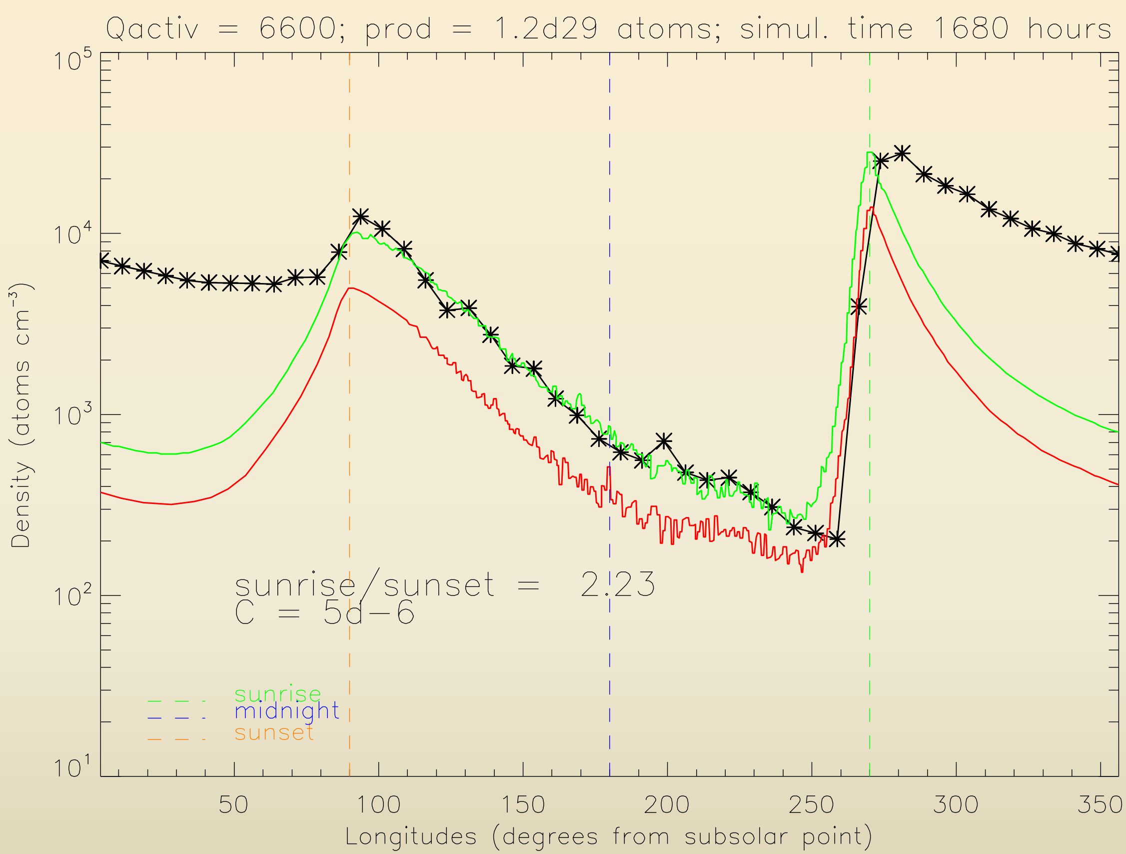


Fig. 7: the average surface temperature is taken from LRO/Diviner radiometer. Rotation of the Moon is taken into account.

Argon simulation – initial run, to reach steady state.

- First time we run the code, we do not include losses, in order to reach steady state.
- We play with Q and C until we find a good agreement with initial measurement of LACE (green line in fig. 8).
- We then adjust the Production.
- Our best parameters are: Qactiv = 6600 cal mole^{-1}; *C* = 5x10^{-6} s K^{-2}; Production = 1.2x10^{29} atoms.

- Fig. 8: the steady state is reached after 70 terrestrial days (black points)



Argon simulation: fitted residence time

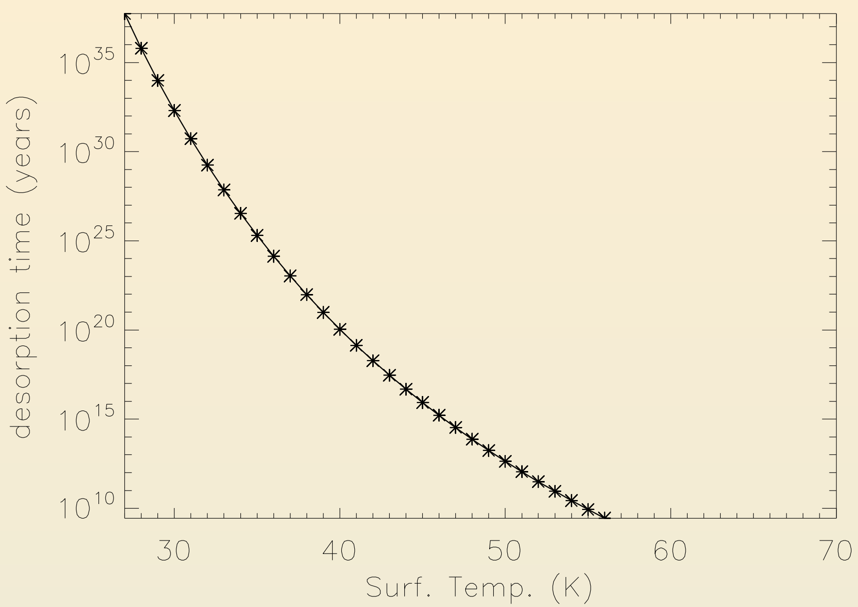
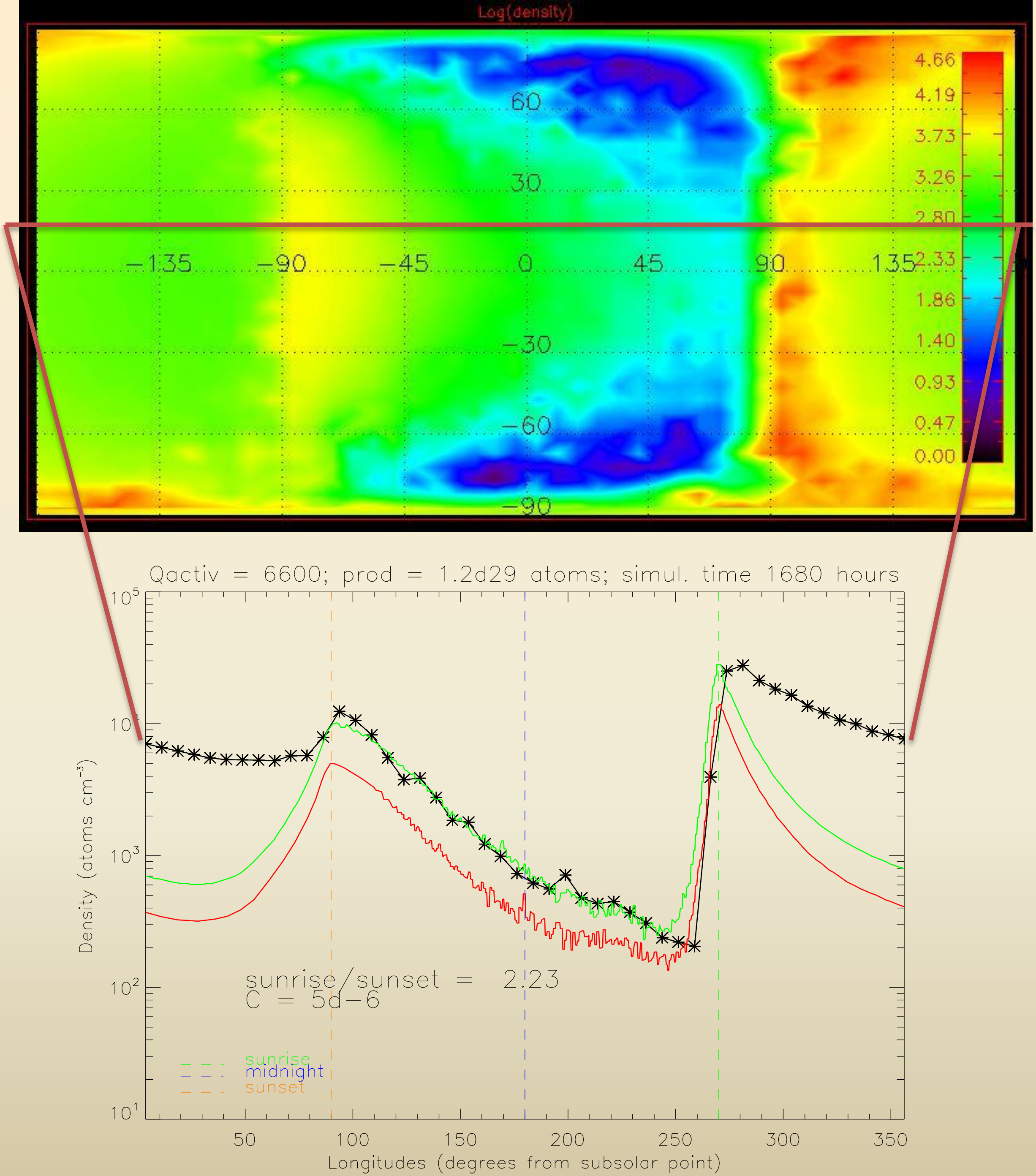


Fig. 9: residence time for temperatures typical of cold traps, calculated using our fitted parameters Q and C.

With the parameters we found (Q = 6600 cal $mole^{-1}$ and C = $5x10^{-6}$ s K^{-2}), the temperature required to retain Argon for 1 Gyr is 56 K.

Argon Simulation: global distribution

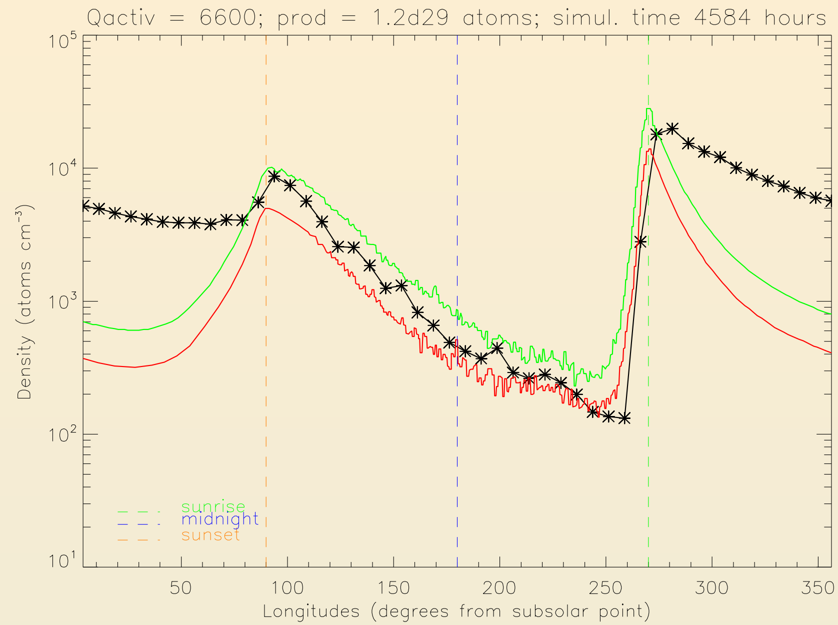


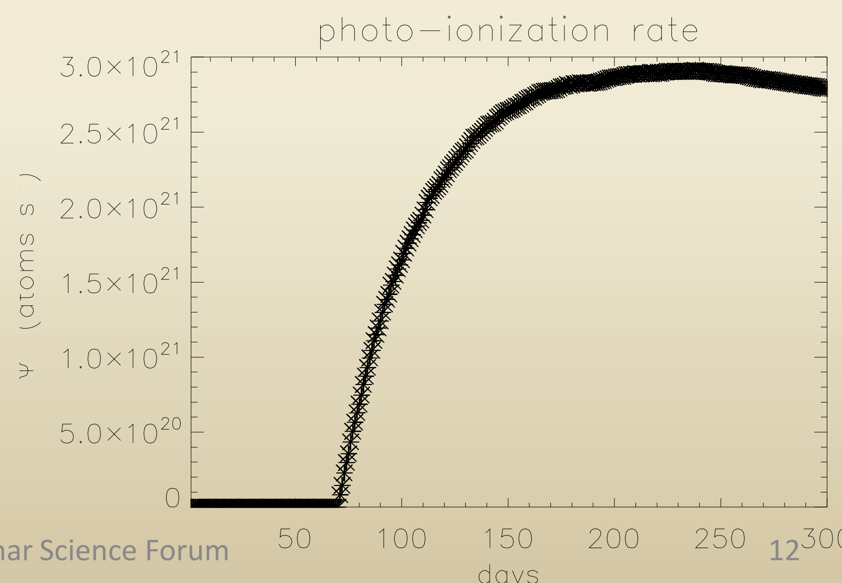
- Fig. 10: Global map of argon density (top, in logarithmic scale) and cut along the latitude of LACE (bottom).

Argon Code: Including solar wind losses

- Next, we included solar wind losses.
- Solar UV photo-ionization is the dominant loss process.
- Charge-exchange with solar wind protons is the next most important process.
- Mean lifetime for these combined processes is 1.5×10^6 s [*Manka & Michel 1971*]
- We recycled 10% of the Ar^+ photo-ions into neutral Ar [*Hodges & Hoffman, 1975*] instead of 50% used by *Manka & Michel [1971]*.
- The solar wind loss is not enough to reproduce the observed decrease after 120 days.
- Other processes are required: cold trapping.

- Fig. 11: top: argon density after 120 days of steady state (black asterisks) does not reach the observed argon density after the same amount of time (red line). Bottom: the photo-ionization rate as a function of time. The curve is initially zero because the simulation has to reach first the steady state; then there is an increase which is not real but an effect of the simulation; the peak and the final decrease is a real effect, and reflects the fact that less and less argon atoms are available for ionization.

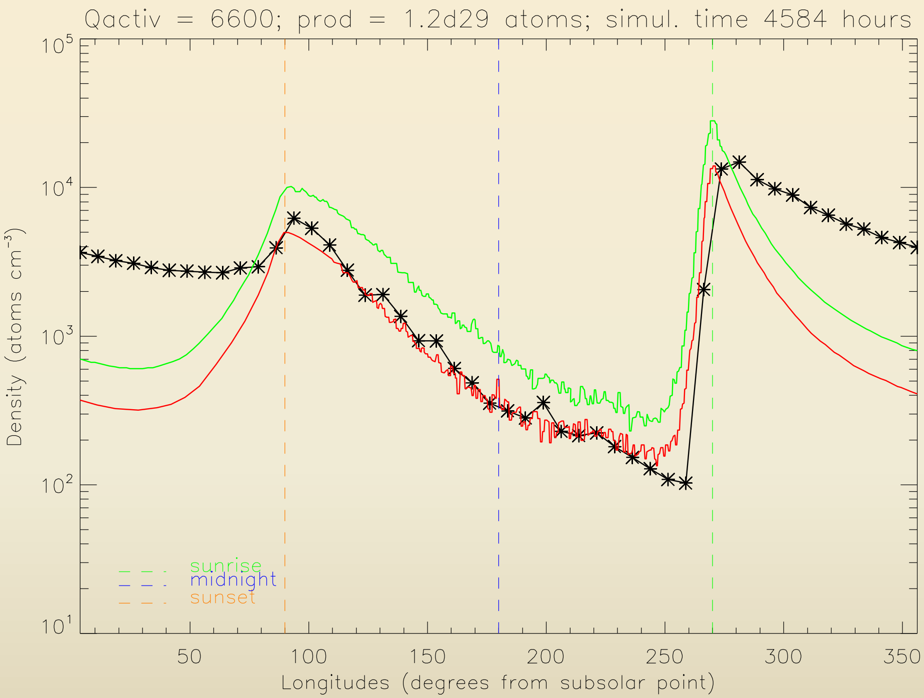




Argon Code: solar wind losses + cold traps

- We add the cold trapping to regions at the poles.
- Cold traps are simulated as regions, at both poles, where a particle is removed from the simulation as soon as it impinges upon one of them;
- The number of these regions is increased until we find an agreement with the observed argon density after 120 days (red line in fig. 12)
- Our preliminary results show that loss of argon atoms by cold-trapping is ~2.5 times faster than solar wind losses: 7.5×10^{21} atoms s^{-1}
- A total of 9.6×10^{28} argon atoms is trapped in 4 months, corresponding to 6.4×10^{3} kg.
- Area of estimated cold traps is 0.26% of total lunar area*. This is higher than the area of PSRs.*

- fig. 12: when we add a certain amount of cold traps (0.26% of lunar surface, in this case), together with the loss by solar wind processes, we find an agreement with the observed argon density (red line) after 4 months from the initial measurements (green line).



Preliminary conclusions and future steps

- Preliminary results shows that cold-trapping flux is ~2.5x higher than loss by photo-ionization and charge exchange. The initial quantity of argon required to fit the initial observed argon density is 8×10^3 kg. This quantity can be released suddenly as a result of a Moonquake or gradually by diffusion; we did not make a distinction here. After 120 months, the amount of argon stored in cold traps is 6.4×10^3 kg.
- In the future, we plan to:
  - investigate non-steady sources (e.g., introduce a varying production rate for argon atoms);
  - Compare the residence time with most recent laboratory results;
  - Compare the cold trap area obtained here (0.26% of lunar surface) with the area occupied by PSRs. This will be accomplished by using several temperature maps instead of the single one used here;
  - Consider long term evolution of argon cold-trapping, applying a space weathering model, like the one of *Crider & Vondrak [2003]*.
  - Calculate brightness of argon line by means of a radiative transfer model and compare it to published upper limits from LRO/LAMP.

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